



Correction of rotational deformity and restoration of thoracic kyphosis are inversely related in posterior surgery for adolescent idiopathic scoliosis

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ABSTRACT

Adolescent Idiopathic Scoliosis (AIS) is a complex three dimensional deformity the treatment of which remains to be surgical correction of the deformity as it had progressed over certain thresholds. The main focus in surgical treatment had, for decades, been the amount of correction in the coronal plane whereas corrections in sagittal and rotational (axial) planes have also been recognized as almost as important as the coronal over the recent decades.

The hypotheses presented and discussed in this study is the virtual adversity between the rates of correction in these two (sagittal and axial) planes. Namely, we are suggesting that due to an elongated anterior spinal column as an intrinsic component of AIS, posterior surgery cannot correct both the axial plane deformity and the thoracic hypokyphosis in the sagittal plane at the same time, unless the posterior spinal column is substantially lengthened. This hypothesis is supported by 3D modeling of the AIS spine as well as the relative inability in changing the sagittal alignment of the thoracic spine demonstrated by a literature search by us.

Understanding and internalization of this hypothesis by AIS surgeons is important as it suggests that by posterior instrumentation, unless a riskier approach of substantially lengthening the spinal column is taken, surgeons need to make the choice of correcting the hypokyphosis OR axial rotation.

Introduction

Adolescent idiopathic scoliosis (AIS) is a complex three-dimensional deformity, and the treatment of this disease has evolved considerably over the past several decades. Currently the gold standard is posterior instrumentation and fusion, with constructs of mainly pedicle screws, but at times of hooks or a combination of the two. While initially there was a focus on achieving maximal correction in the coronal plane, newer techniques have focused on balancing three-dimensional correction in the coronal, sagittal, and axial planes.

Single concave rod derotation technique is one of the most frequently used correction maneuver in AIS surgery. The initial hook based method fell out of favor with the advent of pedicle screw constructs, which quickly became the gold standard in posterior scoliosis surgery. In 2004, Le et al. described direct vertebral body derotation (DVD) technique [1], that gained popularity after several authors reported better axial correction utilizing this technique [2–5].

Thoracic hypokyphosis is commonly seen as an intrinsic feature in AIS, and has been described in association with a compensatory decreased lumbar lordosis leading to flatback syndrome and disabling back pain [6–8]. Several authors have recently advocated for sacrificing some additional correction in the coronal plane in order to more adequately address the sagittal plane [9–11]. While the anterior surgical

approach to treating AIS has shown consistent improvement in thoracic hypokyphosis in this population, the posterior approach, regardless of technique, has not shown the consistent ability to correct this intrinsic deformity [12].

Another feature intrinsic to the AIS spine is a longer anterior spinal column compared to the posterior. Vertebral bodies and intervertebral discs both contribute to this length discrepancy in different proportions. Abnormal vertebral body growth was initially thought to be the reason for this observation, but more recent studies report that the discs contribute more this length difference, suggesting that it is an adaptation mechanism to altered spinal loading [13–15]. In this context, Watanabe et al. demonstrated that kyphosis was reduced after complete correction of the coronal and rotational deformity, in their 3D simulation study. They suggested that vertebral rotation obtained by pedicle screws bring the overgrown anterior vertebral walls anteriorly and increase the length of anterior column at the expense of kyphosis [16].

Despite various individual studies showing good results in the sagittal plane with a posterior surgical approach, the overall results are discordant and average increases in thoracic kyphosis in case series range from -13.9 to $+20$ degrees [17,18]. While there is some literature indicating good results with of hybrid constructs and various adjuvant strategies such as in situ bending maneuvers [11,18], rod rotation maneuvers [19], increased rod stiffness [20,21], and increased

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Table 1
Radiographic outcomes of posterior spinal instrumentation in AIS from 53 original articles included in this study reporting on a total of 3780 patients.

Posterior Spinal Instrumentation in Treatment of AIS: Radiographic Outcomes					
Author	# of Pts	Implant Type/ Comparison Group	Sagittal Plane (T5-T12)		
			Pre-op	Post-op	Correction
Lae Naveaux et al. 2017 (14)	42	PS	24 ± 12	25 ± 8	1
Ilharreborde et al. 2017 (15)	35	PS	6 ± 9	13 ± 8	7
Elnady et al. 2017 (16)	50	PS	38.4 ± 16.7	29.7 ± 11	-8.7
Badve et al. 2017 (17)	16	PS	28.8	23.6	-5.2
	20	PS	26.6	18	-8.6
Lamerain et al. 2017 (18)	45	PS	18.2 ± 10.3	28.2 ± 8.4	10
Pesenti et al. 2016 (19)	34	PS	10.5 ± 7.8	24.1 ± 7.2	13.6
Liu et al. 2015 (12)	18	PS	22.7 ± 7.1	13.8 ± 5.3	-8.9
	17	PS	20.9 ± 4.8	20 ± 6.8	-0.9
	22	PS	22.6 ± 8.96	20.6 ± 8	-2
	20	PS	22 ± 7.8	27.1 ± 5.7	5.1
Liu et al. 2014 (20)	21	PS	15.6 ± 8.9	15.2 ± 5.7	-0.4
	21	HY	19.4 ± 10.2	20.9 ± 6.5	1.5
Hamzaoglu et al. 2013 (21)	89	PS	18	23	5
La Rosa et al. 2013 (22)	51	HY	21 ± 3	32 ± 4	11
Chaiyamongkol et al. 2013 (3)	52	HY	22.2 ± 15.1	27.7 ± 7.8	5.5
Crawford et al. 2013 (23)	34	PS	17.5	18	0.5
	29	HY	22	17	-5
Clement et al. 2012 (9)	27	HY	9	29	20
Krallis et al. 2012 (24)	43	HY	24 ± 14.3	30.7 ± 7	6.7
Blondel et al. 2012 (25)	60	HY	18.7 ± 8	24.8 ± 6	6.1
Hwang et al. 2012 (26)	56	PS	21.7 ± 12.9	17.3 ± 9.0	-4.4
	71	HY	26.3 ± 14.1	19.0 ± 8.3	-7.3
Yilmaz et al. 2012 (27)	35	PS	22.1 ± 13.2	19.9 ± 8.4	-2.2
	35	HY	18.4 ± 11.5	20.0 ± 8.8	1.6
	35	H	20.6 ± 10.3	20.6 ± 6.8	0
Abul-Kasim et al. 2011 (11)	116	PS	15.1 ± 8.1	19.1 ± 6.3	4
Qiu et al. 2011 (10)	24	PS	18.3 ± 10.5	28.3 ± 12.8	10
	24	PS	15.5 ± 12.6	18.4 ± 10.3	2.9
Chunguang et al. 2011 (28)	44	PS	20 ± 8	25 ± 8.0	5
	26	PS	20.4 ± 7.8	28.8 ± 8.6	8.4
Mladenov et al. 2011 (2)	13	PS	13.9 ± 9.7	16.4 ± 8.3	2.5
	17	PS	23.4 ± 9	15.2 ± 6.9	-8.2
Basu et al. 2010 (29)	14	PS	24.4 ± 12.1	11.1 ± 5.6	-13.3
Newton et al. 2010 (1)	83	PS	23.0 ± 12	17.8 ± 7.6	-5.2
Ilharreborde et al. 2010 (30)	75	HY	20.8 ± 11.8	21.2 ± 10	0.4
	75	HY	20.5 ± 9.9	31.8 ± 7.4	11.3
Lonner et al. 2009 (31)	34	PS	26 ± 11	20 ± 7	-6
	33	PS	24 ± 12	24 ± 11	0
	33	HY	27 ± 13	30 ± 9	3
Fu et al. 2009 (32)	39	H	19.7 ± 10.4	21.7 ± 5.5	2
	25	PS	15.8 ± 10.7	13.8 ± 5.4	-2
Sucato et al. 2008 (33)	86	HY	19.3 ± 12.7	18.5 ± 10	-0.8
	132	H	21.9 ± 13	19 ± 8.4	-2.9
Clement et al. 2008 (6)	21	HY	25 ± 14	29 ± 11	4
	23	HY	17 ± 13	30 ± 7	13
Kim et al. 2007 (34)	410	H	23.9 ± 14	19.3 ± 9	-4.6
Lowenstein et al. 2007 (35)	17	PS	29.65 ± 13.8	19.35 ± 8.5	-10.3
	17	HY	26.24 ± 11.2	22.42 ± 10.4	-3.8
Vora et al. 2007 (4)	24	H	30	18	-12
	23	HY	26	28.5	2.5
	25	PS	26	16	-10
Lonner et al. 2006 (36)	23	H	34 ± 10	31 ± 8	-3
Kim et al. 2006 (37)	29	PS	26 ± 14	16 ± 7	-10
	29	HY	30 ± 14	24 ± 14	-6
Kotwicki et al. 2006 (38)	25	H	18.6 ± 11.3	19.5 ± 7.7	0.9
Suk et al. 2005 (39)	203	PS	18 ± 11	23 ± 8	5
Potter et al. 2005 (40)	20	PS	29.4	25	-4.4
Wong et al. 2004 (41)	19	H	18 ± 13	20 ± 8	2
Kim et al. 2004 (8)	26	PS	30.6	16.7	-13.9
	26	H	27.3	21.6	-5.7
Liljenqvist et al. 2002 (42)	49	H	22.3	26.2	3.9
	50	PS	29.6	27.6	-2
Delorme et al. 2002 (43)	44	H	22 ± 14	20 ± 13	-2
Bridwell et al. 2002 (44)	44	H	21 ± 11	19 ± 8	-2
Rhee et al. 2002 (45)	60	HY	25	21	-4

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Table 1 (continued)

Posterior Spinal Instrumentation in Treatment of AIS: Radiographic Outcomes						
Author	# of Pts	Implant Type/ Comparison Group		Sagittal Plane (T5-T12)		
				Pre-op	Post-op	Correction
Wattenbarger et al. 2000 (46)	3	H	King 1 Single Rod	31 ± 9.5	29.7 ± 5.5	-1.3
	9	H	King 2 Single Rod	23 ± 8	23 ± 11	0
	31	H	King 3-5 Single Rod	22.8 ± 11	25.7 ± 8.8	2.9
	9	H	King 1 Dual Rod	31.9 ± 10.4	23 ± 9.8	-8.9
	33	H	King 2 Dual Rod	28.2 ± 13	26.5 ± 11	-1.7
	57	H	King 3-5 Dual Rod	26.7 ± 13	25.0 ± 9.6	-1.7
Albers et al. 2000 (47)	21	H		23 ± 17	27 ± 16	4
Suk et al. 1999 (48)	17	PS		8.1 ± 5.6	27.3 ± 11.3	19.2
	17	H		4.1 ± 8.6	14.5 ± 10.2	10.4
	17	PS		27.3 ± 9.8	28 ± 13.7	0.7
Betz et al. 1999 (49)	100	H		21	22	1
Papin et al. 1999 (50)	30	H		32 ± 18	41 ± 13	9
Takahashi et al. 1997 (51)	30	HR		26 ± 13	30 ± 8	4
Benli et al. 1996 (52)	45	H		20.7	29.6	8.9
Lenke et al. 1994 (53)	27	H	fusion extends to T2	19	18	-1
	27	H	fusion extends to T4	14	22	8
Mason et al. 1991 (54)	24	HR		22.1	17.4	-4.7
	16	H		20.4	20.7	0.3
Bridwell et al. 1990 (55)	84	H	Normokyphotic	29	29	0
	52	H	Hypokyphotic	6	19	9
Richards et al. 1989 (56)	27	H	King 2	29	27	-2
	26	H	King 3	25	22	-3

HR = Harrington Rods, H = Hooks Only, PS = Pedicle Screws, HY = Hybrid Construct

pedicle screw density [22], results have not been consistently reproducible. In a meta-analysis of 24 articles and 1555 patients, Franic et al. reported that posterior treatment of AIS resulted in an average effect of -0.7 ± 2.6 degrees of thoracic kyphosis [12]. Another meta-analysis by Cao et al. reported a positive standard mean difference in sagittal plane correction, with hybrid constructs being more powerful than all pedicle screw constructs. However, the reported standard mean difference of 0.30 indicates a minimal degree of correction (standard mean difference = increase in kyphosis/ standard deviation) [10]. All pedicle screw constructs were reported to have tendency to flatten the thoracic spine, which was not observed in hybrid constructs [23,24]. Posteromedial translation with sublaminar bands has been also shown to be effective in sagittal alignment restoration of hypokyphotic patients [25].

Surgical, restoration of the sagittal plane, especially posterior surgery, has indeed been investigated, and the inability to do so has been mostly attributed to specific conditions such as the correction techniques used (some potentially being better than the others), rod stiffness, pedicle screw density and like [11,18-22]. We are writing this to introduce an hypothesis that these factors, albeit being of some partial importance, conceal the real reason of our inability to correct hypokyphosis by posterior surgery, significantly more so with an increased axial rotation correction, as being the pathoanatomic increased length of the anterior column in AIS.

Hypothesis

We hypothesized that, since the anterior spinal column length is longer than the posterior column in AIS patients, vertebral rotation techniques, actually give rise to a decrease in thoracic kyphosis. Our reasoning follows an analogy of lumbar spinal deformity in which a rotatory subluxation, decreasing the effective length of the anterior column leads to a sudden collapse into kyphosis. Following this line of thought, as the anterior spinal column had become longer than the posterior (through several potential mechanisms discussed above) in the thoracic spine affected by AIS, the observed kyphotic alignment needs to be a function of the axial rotation (torsion) of this region. In this regard, correcting this torsion should lead to a lordotic alignment.

This effect is the opposite of what is desired in sagittal correction of hypokyphotic AIS patients. The exceptions to this phenomenon would be a surgery induced decrease in the length of the anterior column which is achievable through anterior correction of AIS or a surgery induced lengthening of the posterior column through posterior column osteotomies. The former is well described in the literature [12,26]. For the latter though, we only have the work by Watanabe and coworkers who had demonstrated that for comparable coronal plane correction rates, posterior surgery lengthens the spinal column significantly more compared to anterior surgery [27]. This lengthening effect might be virtually undesirable because of the potential danger to neural elements it may introduce.

Evaluation of the hypothesis

Our hypothesis may be proven by a prospective three dimensional analysis (by means of 3D modelling by computerized tomography) of a series of AIS patients pre and postoperatively. Whereas, such a study would introduce unnecessary doses of ionizing radiation to the patients involved for research purposes and thus be unethical. Lower dose solutions such as the EOS system (R) may be alternatives to CT in the near future so as to provide proof to our end. Another alternative would be utilizing an accurate finite element model of the scoliotic spine with all bony and soft tissue structures which does not exist at the time being. These being the tokens of our inability in providing a direct proof to our hypothesis, we reverted to a systematic literature review in order to obtain indirect evidence on the inability of posterior instrumentation techniques regardless of the correction maneuver used, in restoring thoracic kyphosis in AIS patients treated with posterior instrumentation and fusion.

Studies on the use of posterior instrumentation in the surgical correction of adolescent idiopathic scoliosis which reported on pre and post-operative sagittal Cobb angles (T5-T12), enrolled at least 10 patients, and had follow up of at least 12 months were evaluated in this analysis. PubMed database was searched using the keywords "adolescent idiopathic scoliosis," "posterior," and "sagittal." 330 articles were initially identified, and review of the titles and abstracts was undertaken to identify eligible articles for further full text assessment. A total

Table 2
Pooled sagittal deformity correction for posterior instrumentation in the treatment of AIS.

Pooled Sagittal Plane Deformity Correction [N = 3780]	
Avg. Pre-op Sagittal Cobb (°)	22.1
Avg. Post-op Sagittal Cobb (°)	22.6
Avg. Correction (°)	0.5 [−13.9 to +20]

of 53 unique articles ultimately met inclusion criteria and were further evaluated (Table 1) [6–9,11,17–21,23–25,28–67].

The pooled analysis of outcomes reported in the literature with posterior instrumentation and fusion for AIS indicate the overall correction achieved is minimally positive, and not likely to be clinically significant. These results are based on analysis of 3780 total patients, and show an overall average increase in thoracic kyphosis of 0.5 ± 6.8 degrees (Table 2). 54 underwent instrumentation with Harrington rods (HR), 1484 with constructs relying only on hooks (H), 1411 with pedicle screw (PS) constructs, and 831 with hybrid (HY) constructs. Subgroup analysis revealed an increase of 0.4 ± 7.4 degrees in the PS group, 3.0 ± 7.1 in the HY group, and -1.0 ± 4.9 in the H group (Table 3). These results provide indirect support to our hypotheses that regardless of the type of implants (and potentially the correction technique) posterior surgery in AIS cannot correct the hypokyphotic thoracic sagittal alignment. The hypothesized specific inverse relation between the amount of correction in axial rotation (derotation) and an increase in hypokyphosis could not be demonstrated with the available data.

Discussion and consequences of our hypothesis

The results of our systematic review of the literature show that overall increase in thoracic kyphosis was only 0.5 ± 6.8 degrees in AIS patients who underwent posterior instrumentation based hooks, pedicle screws and hybrid constructs. Subgroup analysis revealed that, the increase was 3.0 ± 7.1 degrees and highest in HY group, 0.4 ± 7.4 degrees in the PS group, and -1.0 ± 4.9 degrees in the H group. Despite the evolution of techniques and implants over the years, there has been a failure to provide consistent results in the sagittal plane.

Firstly, the relative lengthening of the anterior column in AIS patients in the course of the deformity development and progression is a recognized phenomenon. Dickson et al. hypothesized that increased anterior vertebral height at the apex of the curve with posterior endplate irregularity, median plane asymmetry, is the primary mechanism of scoliosis development. Thoracic hypokyphosis results in buckling of the spine and coronal plane deformity [68,69]. Guo et al. reported relative anterior spinal overgrowth in AIS patients according to age-matched controls, which mainly occurs by enchondral ossification [70]. Recent studies demonstrated that discs have greater effect on length difference between anterior and posterior spinal column than the vertebral bodies, suggesting that it is an adaptation mechanism, as described in Hueter-Volkman's law, to altered spinal loading rather than primary growth disturbance. In this case, abnormal vertebral growth is a consequence rather than the cause of the deformity [14,15]. In a 3D simulation study, Watanabe et al. reported that kyphosis was reduced after complete correction of the coronal and rotational deformity, but it

Table 3

Sagittal plane correction (change) by procedure type for posterior instrumentation in the treatment of AIS. Note that 'Hooks Only' constructs provide a slight deterioration in thoracic kyphosis whereas hybrid and PS constructs afford for minimal increases.

Sagittal Plane Correction by Procedure Type			
	Pedicle Screws [N = 1411]	Hybrid Construct [N = 831]	Hooks Only [N = 1484]
Sagittal Correction (°)	0.4 ± 7.4	3.0 ± 7.1	-1.0 ± 4.9

was maintained after coronal only correction. They suggested that vertebral derotation causes hypokyphosis of the thoracic spine [16].

Secondly, the inability to restore the sagittal alignment by posterior column surgery in AIS is a problem that is widely recognized. While axial correction improves the cosmetic appearance by reducing the rib hump, thoracic kyphosis correction improves cervical and lumbar balance and reduces the risk of proximal junctional kyphosis and flat back syndrome [25,71,72]. Mladenov et al. reported significantly decreased thoracic kyphosis and lumbar lordosis with DVD while they were remained unchanged with single rod derotation maneuver. They suggested that decreased thoracic kyphosis and lumbar lordosis should be considered in preoperative planning of AIS with DVR. They recommended ultra-hard rods or maneuvers that pull concave side posteriorly to preserve the sagittal alignment of AIS patients [7].

Based on these, it is a wonder why these two bits of information had not been utilized together as the cause and consequence to this date; the inability to restore the sagittal alignment with posterior surgery is the length of the anterior column being longer than the posterior. Recognition of this causality as outlined as an hypothesis here should be expected to have implications on surgical treatment of AIS. As a rule of thumb, in order for a region of the spine to become kyphotic, the anterior column of that region should be rendered shorter than the posterior column. Since as a characteristic of the disease, it is not, the two treatment options would be either shortening of the anterior column so that it becomes shorter than posterior or lengthening the posterior column so that it becomes longer than anterior. Shortening of the anterior column would call for an anterior surgery as the treatment modality or a part of it and in fact it is very well established that this modality is associated with successful restoration of thoracic kyphosis in AIS [12,26]. For the latter option, as we know that some lengthening happens unintentionally anyway [27], the question becomes whether the surgeons should further this spontaneous lengthening in order to achieve a perfect correction of the spinal shape and alignment (presumably by excision of the facet joint capsules and ligamentum flavum at various levels), or settle for a less than ideal correction, both decisions based on what may be more important for the patient;

- Do we want as much correction as possible by lengthening of the spinal column (and thereby potentially increasing the risk of neurological complications)?
- If not necessarily, which aspect should be compromised?
- Should we accept a less than possible rotational correction with residual rib hump for the sake of a more kyphotic thoracic spine? or,
- Should we attempt for a full correction of the rotational deformity and accept thoracic flatback?

In this context, understanding our hypothesis and its clinical implications may prove to be invaluable for improved communications between AIS deformity surgeons and patients and families and in developing a common comprehension of the shape of the patients spinal column following surgery as well as the inherent risks associated with the attainment of a 'perfect' correction.

Declaration of Competing Interest

The authors declare that they have no known competing financial

interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.mehy.2019.109396>.

References

- Lee SM, Suk SI, Chung ER. Direct vertebral rotation: a new technique of three-dimensional deformity correction with segmental pedicle screw fixation in adolescent idiopathic scoliosis. *Spine (Phila Pa)* 1976;2004(29):343–9.
- Tang X, Zhao J, Zhang Y. Radiographic, clinical, and patients' assessment of segmental direct vertebral body derotation versus simple rod derotation in main thoracic adolescent idiopathic scoliosis: a prospective, comparative cohort study. *Eur Spine J* 2015;24:298–305. <https://doi.org/10.1007/s00586-014-3650-y>.
- Pankowski R, Roclawski M, Ceynowa M, Mikulicz M, Mazurek T, Kloc W. Direct Vertebral Rotation Versus Single Concave Rod Rotation: Low-dose Intraoperative Computed Tomography Evaluation of Spine Derotation in Adolescent Idiopathic Scoliosis Surgery. *Spine (Phila Pa)* 1976;2016(41):864–71. <https://doi.org/10.1097/BRS.0000000000001363>.
- Mattila M, Jalanko T, Helenius I. En bloc vertebral column derotation provides spinal derotation but no additional effect on thoracic rib hump correction as compared with no derotation in adolescents undergoing surgery for idiopathic scoliosis with total pedicle screw instrumentation. *Spine (Phila Pa)* 1976;2013(38):1576–83. <https://doi.org/10.1097/BRS.0b013e31829a6d37>.
- Hwang SW, Samdani AF, Lonner B, et al. Impact of direct vertebral body derotation on rib prominence: are preoperative factors predictive of changes in rib prominence? *Spine (Phila Pa)* 1976;2012(37):E86–9. <https://doi.org/10.1097/BRS.0b013e31821fd379>.
- Newton PO, Yaszay B, Upasani VV, et al. Preservation of Thoracic Kyphosis Is Critical to Maintain Lumbar Lordosis in the Surgical Treatment of Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2010(35):1365–70. <https://doi.org/10.1097/brs.0b013e3181dccc63>.
- Mladenov KV, Vaeterlein C, Stuecker R. Selective posterior thoracic fusion by means of direct vertebral derotation in adolescent idiopathic scoliosis: effects on the sagittal alignment. *Eur Spine J* 2011;20:1114–7. <https://doi.org/10.1007/s00586-011-1740-7>.
- Chaiyamongkol W, Klineberg EO, Gupta MC. Apical Wiring Technique in Surgical Treatment of Adolescent Idiopathic Scoliosis: the intermediate outcomes between Lenke types. *J Spinal Disord Tech* 2013;26:E28–34. <https://doi.org/10.1097/bsd.0b013e31827ada52>.
- Vora V, Crawford A, Babekhir N, et al. A Pedicle Screw Construct Gives an Enhanced Posterior Correction of Adolescent Idiopathic Scoliosis When Compared With Other Constructs: myth or reality. *Spine (Phila Pa)* 1976;2007(32):1869–74. <https://doi.org/10.1097/brs.0b013e318108b912>.
- Cao Y, Xiong W, Li F. Pedicle Screw Versus Hybrid Construct Instrumentation in Adolescent Idiopathic Scoliosis: meta-analysis of thoracic kyphosis. *Spine (Phila Pa)* 1976;2014(39):E800–10. <https://doi.org/10.1097/brs.0b013e318108b912>.
- Clement JL, Chau E, Kimpe K, Vallade MJ. Restoration of Thoracic Kyphosis by Posterior Instrumentation in Adolescent Idiopathic Scoliosis: comparative radiographic analysis of two methods of reduction. *Spine (Phila Pa)* 1976;2008(33):1579–87. <https://doi.org/10.1097/brs.0b013e31817886be>.
- Franic M, Tiljak MK, Pozar M, et al. Anterior versus posterior approach in 3D correction of adolescent idiopathic thoracic scoliosis: A meta-analysis. *Orthop Traumatol Surg Res* 2012;98:795–802. <https://doi.org/10.1016/j.otsr.2012.06.014>.
- Modi HN, Suh SW, Song HR, Yang JH, Kim HJ, Modi CH. Differential wedging of vertebral body and intervertebral disc in thoracic and lumbar spine in adolescent idiopathic scoliosis - A cross sectional study in 150 patients. *Scoliosis* 2008;3:11. <https://doi.org/10.1186/1748-7161-3-11>.
- Brink RC, Schlösser TPC, Colo D, et al. Anterior Spinal Overgrowth Is the Result of the Scoliotic Mechanism and Is Located in the Disc. *Spine (Phila Pa)* 1976;2017(42):818–22. <https://doi.org/10.1097/BRS.0000000000001919>.
- Schlösser TPC, van Stralen M, Brink RC, et al. Three-dimensional characterization of torsion and asymmetry of the intervertebral discs versus vertebral bodies in adolescent idiopathic scoliosis. *Spine (Phila Pa)* 1976;2014(39):E1159–66. <https://doi.org/10.1097/BRS.0000000000000467>.
- Watanabe K, Nakamura T, Iwanami A, et al. Vertebral derotation in adolescent idiopathic scoliosis causes hypokyphosis of the thoracic spine. *BMC Musculoskelet Disord* 2012;13:99. <https://doi.org/10.1186/1471-2474-13-99>.
- Kim YJ, Lenke LG, Cho SK, Bridwell KH, Sides B, Blanke K. Comparative Analysis of Pedicle Screw Versus Hook Instrumentation in Posterior Spinal Fusion of Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2004(29):2040–8. <https://doi.org/10.1097/01.brs.0000138268.12324.1a>.
- Clement JL, Chau E, Geoffray A, Vallade MJ. Simultaneous Translation on Two Rods to Treat Adolescent Idiopathic Scoliosis: radiographic results in coronal, sagittal, and transverse plane of a series of 62 patients with a minimum follow-up of two years. *Spine (Phila Pa)* 1976;2012(37):184–92. <https://doi.org/10.1097/brs.0b013e3182155104>.
- Qiu Y, Zhu F, Wang B, et al. Comparison of Surgical Outcomes of Lenke Type 1 Idiopathic Scoliosis: vertebral coplanar alignment versus derotation technique. *J Spinal Disord Tech* 2011;24:492–9. <https://doi.org/10.1097/bsd.0b013e3182060337>.
- Abul-Kasim K, Karlsson MK, Ohlin A. Increased rod stiffness improves the degree of deformity correction by segmental pedicle screw fixation in adolescent idiopathic scoliosis. *Scoliosis* 2011;6:13. <https://doi.org/10.1186/1748-7161-6-13>.
- Liu H, Li Z, Li S, et al. Main thoracic curve adolescent idiopathic scoliosis: association of higher rod stiffness and concave-side pedicle screw density with improvement in sagittal thoracic kyphosis restoration. *J Neurosurg Spine* 2015;22:259–66. <https://doi.org/10.3171/2014.10.spine1496>.
- Sweet FA, Lenke LG, Bridwell KH, Blanke KM, Whorton J. Prospective Radiographic and Clinical Outcomes and Complications of Single Solid Rod Instrumented Anterior Spinal Fusion in Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2001(26):1956–65. <https://doi.org/10.1097/00007632-200109150-00005>.
- Lowenstein JE, Matsumoto H, Vitale MG, et al. Coronal and sagittal plane correction in adolescent idiopathic scoliosis: a comparison between all pedicle screw versus hybrid thoracic hook lumbar screw constructs. *Spine (Phila Pa)* 1976;2007(32):448–52. <https://doi.org/10.1097/01.brs.0000255030.78293.fid>.
- Kim YJ, Lenke LG, Kim J, et al. Comparative Analysis of Pedicle Screw Versus Hybrid Instrumentation in Posterior Spinal Fusion of Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2006(31):291–8. <https://doi.org/10.1097/01.brs.0000197865.20803.d4>.
- Ilharreborde B, Pesenti S, Ferrero E, et al. Correction of hypokyphosis in thoracic adolescent idiopathic scoliosis using sublamina bands: a 3D multicenter study. *Eur Spine J* 2018;27:350–7. <https://doi.org/10.1007/s00586-017-5166-8>.
- Lin Y, Chen W, Chen A, Li F, Xiong W. Anterior versus Posterior Selective Fusion in Treating Adolescent Idiopathic Scoliosis: A Systematic Review and Meta-Analysis of Radiologic Parameters. *World Neurosurg* 2018;111:e830–44. <https://doi.org/10.1016/j.wneu.2017.12.161>.
- Watanabe K, Hosogane N, Kawakami N, et al. Increase in spinal longitudinal length by correction surgery for adolescent idiopathic scoliosis. *Eur Spine J* 2012;21:1920–5. <https://doi.org/10.1007/s00586-012-2163-9>.
- Le Navéaux F, Labelle H, Parent S, Newton PO, Aubin CE. Are There 3D Changes in Spine and Rod Shape in the 2 Years After Adolescent Idiopathic Scoliosis Instrumentation? *Spine (Phila Pa)* 1976;2017(42):1158–64. <https://doi.org/10.1097/brs.00000000000002056>.
- Crawford AH, Lykissas MG, Gao X, Eismann E, Anadio J. All-Pedicle Screw Versus Hybrid Instrumentation in Adolescent Idiopathic Scoliosis Surgery: a comparative radiographic study with a minimum 2-year follow-up. *Spine (Phila Pa)* 1976;2013(38):1199–208. <https://doi.org/10.1097/brs.0b013e31828ce597>.
- Krallis P, Thoma S, Kosmidis I, Kyriakopoulos G, Hager I. Hybrid instrumentation for correction of adolescent idiopathic scoliosis. *Acta Orthop Belg* 2012;78:94–9.
- Blondel B, Lafage V, Farcy JP, Schwab F, Bollini G, Jouve JL. Influence of screw type on initial coronal and sagittal radiological correction with hybrid constructs in adolescent idiopathic scoliosis. Correction priorities. *Orthop Traumatol Surg Res* 2012;98:873–8. <https://doi.org/10.1016/j.otsr.2012.09.005>.
- Hwang SW, Samdani AF, Wormser B, et al. Comparison of 5-year outcomes between pedicle screw and hybrid constructs in adolescent idiopathic scoliosis. *J Neurosurg Spine* 2012;17:212–9. <https://doi.org/10.3171/2012.6.spine1215>.
- Yilmaz G, Borkhuu B, Dhawale AA, et al. Comparative Analysis of Hook, Hybrid, and Pedicle Screw Instrumentation in the Posterior Treatment of Adolescent Idiopathic Scoliosis. *J Pediatr Orthop* 2012;32:490–9. <https://doi.org/10.1097/bpo.0b013e318250c629>.
- Chunguang Z, Yueming S, Limin L, et al. Convex Short Length Rib Resection in Thoracic Adolescent Idiopathic Scoliosis. *J Pediatr Orthop* 2011;31:757–63. <https://doi.org/10.1097/bpo.0b013e31822f9070>.
- Elnady B, El-Sharkawi MM, El-Meshtawy M, Adam FF, Said GZ. Posterior-only surgical correction of adolescent idiopathic scoliosis: an Egyptian experience. *SICOT J* 2017;3:69. <https://doi.org/10.1051/sicotj/2017057>.
- Basu S, Rathinavelu S, Baid P. Posterior scoliosis correction for adolescent idiopathic scoliosis using side-opening pedicle screw-rod system utilizing the axial translation technique. *Indian J Orthop* 2010;44:42. <https://doi.org/10.4103/0019-5413.58605>.
- Ilharreborde B, Even J, Lefevre Y, et al. Hybrid Constructs for Tridimensional Correction of the Thoracic Spine in Adolescent Idiopathic Scoliosis: a comparative analysis of universal clamps versus hooks. *Spine (Phila Pa)* 1976;2010(35):306–14. <https://doi.org/10.1097/brs.0b013e3181b7c7e4>.
- Lonner BS, Auerbach JD, Boachie-Adjei O, Shah SA, Hosogane N, Newton PO. Treatment of Thoracic Scoliosis: are monoaxial thoracic pedicle screws the best form of fixation for correction? *Spine (Phila Pa)* 1976;2009(34):845–51. <https://doi.org/10.1097/brs.0b013e31819e2753>.
- Fu G, Kawakami N, Goto M, Tsuji T, Ohara T, Imagama S. Comparison of Vertebral Rotation Corrected by Different Techniques and Anchors in Surgical Treatment of Adolescent Thoracic Idiopathic Scoliosis. *J Spinal Disord Tech* 2009;22:182–9. <https://doi.org/10.1097/bsd.0b013e318177028b>.
- Sucato DJ, Agrawal S, O'Brien MF, Lowe TG, Richards SB, Lenke L. Restoration of Thoracic Kyphosis After Operative Treatment of Adolescent Idiopathic Scoliosis: a multicenter comparison of three surgical approaches. *Spine (Phila Pa)* 1976;2008(33):2630–6. <https://doi.org/10.1097/brs.0b013e3181880498>.
- Kim YJ, Lenke LG, Bridwell KH, et al. Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis After 3 Different Types of Posterior Segmental Spinal

- Instrumentation and Fusions: incidence and risk factor analysis of 410 cases. *Spine (Phila Pa)* 1976;2007(32):2731–8. <https://doi.org/10.1097/brs.0b013e31815a7ead>.
- [42] Badve SA, Goodwin RC, Gurd D, Kuivila T, Kurra S, Lavelle WF. Uniplanar Versus Fixed Pedicle Screws in the Correction of Thoracic Kyphosis in the Treatment of Adolescent Idiopathic Scoliosis (AIS). *J Pediatr Orthop* 2017;37:e558–62. <https://doi.org/10.1097/bpo.0000000000000927>.
- [43] Lonner BS, Kondrachov D, Siddiqi F, Hayes V, Scharf C. Thoracoscopic spinal fusion compared with posterior spinal fusion for the treatment of thoracic adolescent idiopathic scoliosis. *J Bone Joint Surg Am.* 2006;88:1022–34. <https://doi.org/10.2106/00004623-200605000-00013>.
- [44] Suk SI, Lee SM, Chung ER, Kim JH, Kim SS. Selective Thoracic Fusion With Segmental Pedicle Screw Fixation in the Treatment of Thoracic Idiopathic Scoliosis: more than 5-year follow-up. *Spine (Phila. Pa)* 1976;2005(30):1602–9. <https://doi.org/10.1097/01.brs.0000169452.50705.61>.
- [45] Kotwicki T, Dubousset J, Padovani JP. Correction of flexible thoracic scoliosis below 65 degrees—a radiological comparison of anterior versus posterior segmental instrumentation applied to similar curves. *Eur Spine J* 2006;15:972–81. <https://doi.org/10.1007/s00586-005-0991-6>.
- [46] Potter BK, Kuklo TR, Lenke LG. Radiographic Outcomes of Anterior Spinal Fusion Versus Posterior Spinal Fusion With Thoracic Pedicle Screws for Treatment of Lenke Type I Adolescent Idiopathic Scoliosis Curves. *Spine (Phila Pa)* 1976;2005(30):1859–66. <https://doi.org/10.1097/01.brs.0000174118.72916.96>.
- [47] Wong HK, Hee HT, Yu Z, Wong D. Results of Thoracoscopic Instrumented Fusion versus Conventional Posterior Instrumented Fusion in Adolescent Idiopathic Scoliosis Undergoing Selective Thoracic Fusion. *Spine (Phila Pa)* 1976;2004(29):2031–8. <https://doi.org/10.1097/01.brs.0000138304.77946.ea>.
- [48] Liljenqvist U, Lepsien U, Hackenberg L, Niemeier T, Halm H. Comparative analysis of pedicle screw and hook instrumentation in posterior correction and fusion of idiopathic thoracic scoliosis. *Eur Spine J* 2002;11:336–43. <https://doi.org/10.1007/s00586-002-0415-9>.
- [49] Delorme S, Labelle H, Aubin CE. Is Cobb angle progression a good indicator in adolescent idiopathic scoliosis? *Spine (Phila Pa)* 1976;2002(27):E145–51. <https://doi.org/10.1097/00007632-200203150-00009>.
- [50] Bridwell KH, Hanson DS, Rhee JM, Lenke LG, Baldus C, Blanke K. Correction of Thoracic Adolescent Idiopathic Scoliosis With Segmental Hooks, Rods, and Wisconsin Wires Posteriorly: it's bad and obsolete, correct? *Spine (Phila Pa)* 1976;2002(27):2059–66. <https://doi.org/10.1097/00007632-200209150-00018>.
- [51] Lamerain M, Bachy M, Dubory A, Kabbaj R, Scemama C, Vialle R. All-Pedicle Screw Fixation With 6-mm-Diameter Cobalt-Chromium Rods Provides Optimized Sagittal Correction of Adolescent Idiopathic Scoliosis. *Clin Spine Surg* 2017;30:E857–63. <https://doi.org/10.1097/bsd.0000000000000413>.
- [52] Rhee JM, Bridwell KH, Won DS, Lenke LG, Chotigavanichaya C, Hanson DS. Sagittal Plane Analysis of Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2002(27):2350–6. <https://doi.org/10.1097/00007632-200211010-00008>.
- [53] Wattenbarger JM, Richards BS, Herring JA. A Comparison of Single-Rod Instrumentation With Double-Rod Instrumentation in Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2000(25):1680–8. <https://doi.org/10.1097/00007632-200007010-00011>.
- [54] Albers HW, Hresko MT, Carlson J, Hall JE. Comparison of Single- and Dual-Rod Techniques for Posterior Spinal Instrumentation in the Treatment of Adolescent Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;2000(25):1944–9. <https://doi.org/10.1097/00007632-200008010-00013>.
- [55] Suk SI, Kim WJ, Kim JH, Lee SM. Restoration of thoracic kyphosis in the hypokyphotic spine: a comparison between multiple-hook and segmental pedicle screw fixation in adolescent idiopathic scoliosis. *J Spinal Disord* 1999;12:489–95. <https://doi.org/10.1097/00002517-199912000-00008>.
- [56] Papin P, Labelle H, Delorme S, Aubin CE, de Guise JA, Dansereau J. Long-term three-dimensional changes of the spine after posterior spinal instrumentation and fusion in adolescent idiopathic scoliosis. *Eur Spine J* 1999;8:16–21. <https://doi.org/10.1007/s005860050121>.
- [57] Betz RR, Harms J, Clements DH, et al. Comparison of Anterior and Posterior Instrumentation for Correction of Adolescent Thoracic Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;1999(24):225–39. <https://doi.org/10.1097/00007632-199902010-00007>.
- [58] Takahashi S, Delécrin J, Passuti N. Changes in the Unfused Lumbar Spine in Patients With Idiopathic Scoliosis. A 5- to 9-year assessment after cotel-dubousset instrumentation. *Spine (Phila Pa)* 1976;1997(22):517–23. <https://doi.org/10.1097/00007632-199703010-00009>.
- [59] Benli IT, Tuzuner M, Akalin S, Kis M, Aydin E, Tandogan R. Spinal imbalance and decompensation problems in patients treated with Cotel-Dubousset instrumentation. *Eur Spine J* 1996;5:380–6. <https://doi.org/10.1007/bf00301965>.
- [60] Lenke LG, Bridwell KH, O'Brien MF, Baldus C, Blanke K. Recognition and Treatment of the Proximal Thoracic Curve in Adolescent Idiopathic Scoliosis Treated with Cotel-Dubousset Instrumentation. *Spine (Phila Pa)* 1976;1994(19):1589–97. <https://doi.org/10.1097/00007632-199407001-00007>.
- [61] Mason DE, Carango P. Spinal Decompensation in Cotel-Dubousset Instrumentation. *Spine (Phila Pa)* 1976;1991(16):394–403. <https://doi.org/10.1097/00007632-199108001-00018>.
- [62] Pesenti S, Chalopin A, Peltier E, et al. How Sublaminar Bands Affect Postoperative Sagittal Alignment in AIS Patients with Preoperative Hypokyphosis? Results of a Series of 34 Patients with 2-Year Follow-Up. *Biomed Res Int* 2016;2016:1954712. <https://doi.org/10.1155/2016/1954712>.
- [63] Bridwell KH, Betz R, Capelli AM, Huss G, Harvey C. Sagittal Plane Analysis in Idiopathic Scoliosis Patients Treated with Cotel-Dubousset Instrumentation. *Spine (Phila Pa)* 1976;1990(15):921–6. <https://doi.org/10.1097/00007632-199009000-00016>.
- [64] Richards BS, Birch JG, Herring JA, Johnston CE, Roach JW. Frontal Plane and Sagittal Plane Balance following Cotel-Dubousset Instrumentation for Idiopathic Scoliosis. *Spine (Phila Pa)* 1976;1989(14):733–7. <https://doi.org/10.1097/00007632-198907000-00015>.
- [65] Liu T, Hai Y. Sagittal Plane Analysis of Selective Posterior Thoracic Spinal Fusion in Adolescent Idiopathic Scoliosis: a comparison study of all pedicle screw and hybrid instrumentation. *J Spinal Disord Tech* 2014;27:277–82. <https://doi.org/10.1097/01.bsd.0000451597.91287.a0>.
- [66] Hamzaoglu A, Ozturk C, Enercan M, Alanay A. Traction X-ray under general anesthesia helps to save motion segment in treatment of Lenke type 3C and 6C curves. *Spine J* 2013;13:845–52. <https://doi.org/10.1016/j.spinee.2013.03.043>.
- [67] La Rosa G, Giglio G, Oggiano L. The Universal Clamp hybrid system: a safe technique to correct deformity and restore kyphosis in adolescent idiopathic scoliosis. *Eur Spine J* 2013;22:823–8. <https://doi.org/10.1007/s00586-013-3014-z>.
- [68] Dickson RA, Lawton JO, Archer IA, Butt WP. The pathogenesis of idiopathic scoliosis. Biplanar spinal asymmetry. *J Bone Joint Surg Br* 1984;66:8–15.
- [69] Dickson RA. The etiology and pathogenesis of idiopathic scoliosis. *Acta Orthop Belg* 1992;58(Suppl 1):21–5.
- [70] Guo X, Chau WW, Chan YL, Cheng JC. Relative anterior spinal overgrowth in adolescent idiopathic scoliosis. Results of disproportionate endochondral-membranous bone growth. *J Bone Joint Surg Br* 2003;85:1026–31.
- [71] Ilharborde B, Vidal C, Skalli W, Mazda K. Sagittal alignment of the cervical spine in adolescent idiopathic scoliosis treated by posteromedial translation. *Eur Spine J* 2013;22:330–7. <https://doi.org/10.1007/s00586-012-2493-7>.
- [72] Charles YP, Sfeir G, Matter-Parrat V, Sauleau EA, Steib JP. Cervical sagittal alignment in idiopathic scoliosis treated by posterior instrumentation and in situ bending. *Spine (Phila Pa)* 1976;2015(40):E419–27. <https://doi.org/10.1097/BRS.0000000000000767>.